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ORIGINAL PAPER

Optimizing any-aged management of mixed boreal forest under residual basal area constraints

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Abstract: The current trend of forest management in many countries is reduced use of clear-felling and planting, and increased use of continuous cover management. In Finland, the new forest act of 2014 made all types of cuttings equally allowable on the condition that if the post-cutting residual stand basal area is too low, the stand must be regenerated within certain time frame. Forest landowner can freely choose between even- and uneven-aged management. This study developed a method for optimizing the timing and type of cuttings without the need to categorize the management system as either even-aged or uneven-aged. A management system that does not set any requirements on the sequence of post-cutting diameter distributions is called any-aged management. Planting or sowing was used when stand basal area fell below the required minimum basal area and the amount of advance regeneration was less than required in the regulations. When the cuttings of 200 stands managed earlier with even-aged silviculture were optimized with the developed system, final felling followed by artificial regeneration was selected for almost 50% of stands. Reduction of the minimum basal area limit greatly decreased the use of artificial regeneration but improved profitability, suggesting that the truly optimal management would be to use natural regeneration in financially mature stands. The optimal type of thinning was high thinning in 97–99 % of cases. It was calculated that the minimum basal area requirement reduced the mean net present value of the stands by 12–16 % when discount rate was 3–5 %.

Keywords: any-aged silviculture, artificial regeneration, continuous cover forestry, optimal management, uneven-aged management

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Introduction

Despite several decades of even-aged management (Kuuluvainen et al. 2012), Finnish forests include many types of stand structures, forming a continuum from strictly even-aged to clearly uneven-aged stands (Laiho et al. 2011). An important factor contributing to uneven-aged and heterogeneous stand structures is the advance regeneration of spruces under canopies of shade-intolerant species. This regeneration often begins already at young stand age, resulting in mixed stands in which spruces are younger and smaller than pines and broadleaves. However, also pine and broadleaved species may regenerate under sparse canopies of any species, increasing the number of different forest structures.

Finnish forest management is changing into more liberal direction. The latest forest act was issued in the beginning of 2014 and it brought about a few relevant changes in the regulation of forest management (Anonym 2013). For example, both high and low thinning are now allowed without any preference to a particular thinning method. The stand can be regenerated at any age or diameter, and uneven-aged management can be started with forest landowner's decision. However, there are some important regulations concerning the minimum stand basal area that must be retained in cutting. If this legal limit is not met, the cutting is interpreted as final felling, after which the stand must be regenerated within a certain time frame. In south Finland, a 50-cm high seedling stands must be obtained in 10 years after final felling. The new regeneration must be dense enough and stocked with tree species that are regarded productive from timber production point of view.

The new situation is challenging for forest management practice since management prescriptions can no longer be derived directly from legislation and other regulations. This has increased the need for case-by-case economic analyses. There is more freedom to pursue economically optimal management, but there is not enough knowledge about the optimal management of different stand types.

Management decisions are more complicated than selecting

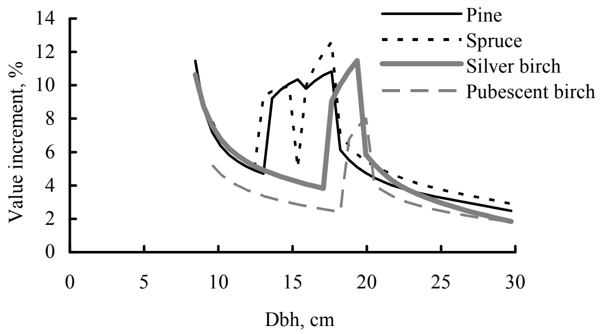
between low and high thinning, or using either even- or uneven-aged management (Haight and Monserud 1990b). For example, it may be economically optimal to use even-aged management in a mature even-aged stand at first, so as to regenerate the stand quickly, but use uneven-aged management thereafter (Tahvonen et al. 2010). In mixed stands where spruces are smaller than pines and broadleaves it may be optimal to start with several high thinnings, which represent uneven-aged management, but eventually conduct a strong regenerative cut once the stand has converted into pure spruce stand, which regenerates poorly. In uneven-aged management, it may be optimal to have a non-constant fluctuating sequence of residual stand densities (Haight 1985, Haight et al. 1985, Pukkala et al. 2012).

Selecting the trees that are removed in thinning and deciding the proper time of cutting are related to the value increment of trees (Knoke 2012). After the juvenile period, the relative volume increment of a tree begins to decrease as a function of age and tree size. If timber price is constant, relative value increment behaves in the same way. The tree becomes financially mature for felling once its relative value increment falls below the market rate of interest. Thinning is conducted when there are enough financially mature trees for an efficient harvesting operation. Although this simple rule is modified by the value of bare land and the effect of tree removal on the growth of remaining trees, optimization would still be easy.

However, the existence of different timber assortments and their unequal prices make the decision on tree removal more complicated and even specific to individual timber sales because the assortments and their unit prices are agreed between timber seller and buyer. The traditional timber assortments in Finland are saw log and pulpwood. Some buyers also buy so-called mini logs or balks of pine and spruce, which are between saw logs and pulpwood pieces in size and price.

The volumes of timber assortments change instantly when their minimum dimensions (top diameter and piece length) are reached, causing an instantaneous change in stem value. Trees approaching an instantaneous change in assortment volumes may have a very high relative value increment. These trees produce the highest economic benefit and should therefore be left to continue growing in thinning treatments. In confers, the most productive diameter range is 13–20 cm if mini logs are sold (Fig. 1). In birch, the corresponding diameter range is 17–22 cm if mini logs are not sold and the top diameter of a saw log is 2–3 cm larger than with conifers.

The non-smooth relative value increment as a function of diameter makes the selection of removed trees complicated. It seems clear that the largest trees are the most mature and should be removed. However, it is less clear whether some smaller trees which are not yet close to any value threshold should be removed as well. Some optimizations for even-aged management suggest that it may be optimal to remove trees from both ends of the diameter distribution and leave medium-sized trees with a high relative value increment to continue growing (Pukkala et al. 1998, Hyytiäinen et al. 2005). However, the conclusion may be different if switching to uneven-aged management is included in optimization as a potential management alternative.



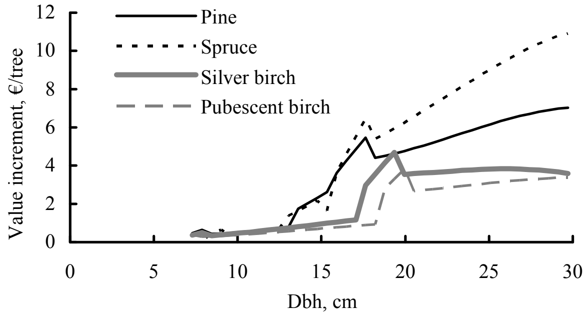


Fig 1: Relative and absolute value increment of different tree sizes in an uneven-sized stand of Scots pine, Norway spruce, silver birch and pubescent birch. The value increment is the mean annual value increment during the next 10 years. In the top diagram, it is expressed as percent of the stem value in the beginning of the 10-year period.

If all trees of a stand have the same diameter, and clearfelling is the only cutting type, the right time to cut trees is the when the value increment of trees is equal to the opportunity cost of growing stock and bare land. The same principle applies also to the thinning of an uneven-aged forest. If bare land value is zero, the relative value increment of trees of different sizes provides useful information for tree removal (Fig. 1, top). However, also the absolute value increment (Fig. 1, bottom) matters at higher bare land values. The diameter of financial maturity is larger on better sites, or stand density should be higher on better sites. The optimal choice of the time, intensity and type of cutting is further complicated by the effect of tree removal on the productivity of remaining trees and the dependence of harvesting costs on the volume and size of harvested trees.

The above discussion suggests it is not easy to develop simple rules for tree removal on the basis of the value increment of trees. Therefore, stand-specific optimization calculations are needed. The aim of this study was to develop such a system for stand management optimization, which does not require any pre-selection between even- and uneven-aged management. The method was used to optimize the timing, type and intensity of cuttings with the restriction that the stand must be regenerated if stand basal area decreases below the minimum acceptable value (legal limit). The obtained management prescriptions are called any-aged management because cuttings or management schedules are newer categorized to represent either even- or uneven-aged management, and alterations between even-aged and

uneven-aged types of cutting are allowed (Haight and Monserud 1990a). Any-aged management refers a series of cuttings that does not set any requirements for the sequence of post-cutting diameter distributions. Planting additional trees on the harvesting site is a part of any-aged management. Whereas Haight and Monserud (1990b) optimized the number of tree planted after cutting, this study assumed that artificial regeneration must be done whenever the post-cutting stand basal area falls below the minimum allowed basal area.

The first part of the study analyzes the influence of problem formulation, i.e., complexity of the optimization problem, on the quality of solution, aiming at finding a formulation which is not unnecessarily complicated but results in a profitable management schedule. Simple formulations are faster to solve and easier to implement and understand. After finding the best way to formulate the optimization problem, management is optimized for a high number of stands, and the type of optimal management as a function of stand structure is discussed. The impact of legal limits on optimal management is also analyzed.

Material and methods

Two forests were selected for the analyses, one representing south–central Finland (temperature sum 1200 d.d.) and the other representing north–central Finland (1000 d.d). One hundred first stands with mean diameter at least 10 cm and stand basal area at least 15 m^2/ha were selected from both forests. These are stands in which it may be optimal to conduct a cutting in the near future. In the past, both forests have been managed using even-aged silviculture and mainly low thinnings. The forests contain many financially mature stands, which have already passed the typical stand age and mean tree diameter of final felling.

In the new forest act of Finland (Anonym 2013), the legal limits, i.e., the minimum post-thinning stand basal area, are given separately for even-aged and uneven-aged forest management. They range from 7 to 13 $m^2 \cdot ha^{-1}$, depending on growing site and silvicultural system. Since this study assumed no explicit choice between even- and uneven-aged management, the law could not be applied literally. In this study, the regulations for minimum post-thinning basal area were assumed to be as follows:

- herb rich site: 13 $m^2 \cdot ha^{-1}$
- mesic site: 12 $m^2 \cdot ha^{-1}$
- sub-xeric site: 10 $m^2 \cdot ha^{-1}$
- xeric site: 8 $m^2 \cdot ha^{-1}$

These limits were included in the simulation so that whenever the post-thinning basal area was below the lowest allowed stand basal area, the cutting was interpreted as a final cut, leading to the obligation to regenerate the stand. It was first inspected whether the number of remaining trees was sufficient without planting or sowing. If this was the case, no site preparation and artificial regeneration was simulated. The regulations concerning the acceptance of different tree species were taken into account when evaluating the sufficiency of the regeneration. The regulations state, among other things, that the share of *B. pubescence* may be maximally 20% of the seedlings that are included in the tree count.

If advance regeneration was insufficient, cleaning of the regeneration site, site preparation and artificial regeneration were simulated. A tending treatment of the young stand was simulated 10 years after regeneration. The regeneration method was sowing pine on poor growing sites, or planting spruce on fertile and medium sites. Regeneration cost (including pre-commercial tending) ranged from 700 to 1700 € ha^{-1} depending on site, regeneration method, the need to clean the site, and existence of residual trees.

If the post-cutting stand included pulpwood- and saw-log-sized trees, they were not removed in the cleaning of the regeneration site. It was assumed that site preparation destroys 50% of any existing trees of the regeneration site. Site preparation cost was assumed to increase linearly with increasing residual basal area so that each 3 $m^2 \cdot ha^{-1}$ increased the cost by 10%. It was also assumed that high thinning destroys a part of advance regeneration so that the percentage of destruction increases linearly as a function of removed volume equaling 100% at 800 $m^3 \cdot ha^{-1}$.

The models of Pukkala et al. (2013) were used to simulate stand development. The model set includes distance-independent models for diameter increment and tree survival, and a model for ingrowth (advance regeneration). The models have been shown to give unbiased predictions in both even- and uneven-aged stands (Pukkala et al. 2013). The height models of Pukkala et al. (2009) and the taper models of Laasasenaho (1982) were used to calculate the assortment volumes of removed trees. The models of Mehtätalo (2002) were used to calculate the deductions in saw log volume due to quality defects. However, the predictions of Mehtätalo's models were corrected with the empirical multipliers obtained from Malinen et al. (2007). The used minimum dimensions of timber assortments, as well as their roadside prices are shown in Table 1.

Table 1: Minimum dimensions and roadside prices of different timber assortments.

		Pine	Spruce	Birch
Minimum top diameter, cm	Saw log	15	16	18
	mini log	13	13	-
	pulp wood	7	8	7
Minimum piece length, m	saw log	4.3	4.3	3.4
	mini log	4.3	4.3	-
	pulp wood	3.0	3.0	3.0
Stumpage price, €/m^3	saw log	55	55	43
	mini log	27	27	-
	pulp wood	17	18	17
Roadside price, €/m^3	saw log	58	58	45
	mini log	39	39	-
	pulp wood	30	31	30

The net incomes of cutting were calculated as the difference between roadside value of harvested trees (Table 1) and harvesting costs (Valsta 1992), which depended on the mean size of

harvested trees and harvested volume per hectare. Harvesting costs were lower in final felling than in thinning (Valsta 1992). Although decreasing unit cost of harvesting with increasing removal was taken into account in the harvesting cost function, it was required that the removal of each cutting must be at least 50 m^3ha^{-1}.

Four alternatives to formulate the optimization problem were compared:

- thinning intensity curve (3 parameters)
- step-wisely linear thinning intensity (4 parameters)
- thinning intensity by 5-cm dbh classes (5 parameters)
- spline-smoothed thinning intensity by dbh classes (5 parameters)

In the first method, the following logistic function was used to express the thinning intensity as a function of diameter

$$p = \frac{1}{(1 + a_1 \exp(-a_2(d - a_3)))^{1/a_1}} \tag{1}$$

where p is the proportion of removed trees, d is diameter at breast height (cm), and a_1, a_2 and a_3 are the optimized parameters, which define the intensity and type of thinning (Fig. 2).

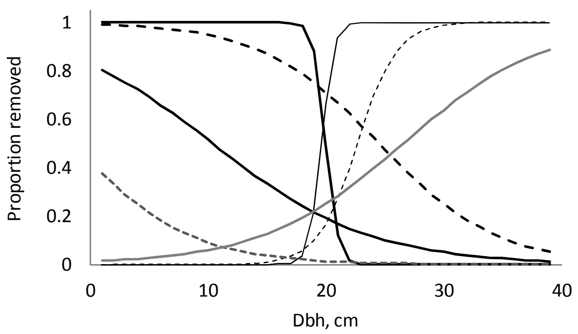


Fig. 2: Examples of thinning intensity curves based on Equation 1 with different values of a_1, a_2 and a_3.

The step-wisely linear thinning intensity function was defined by two points (two diameters and two thinning intensities, i.e., 4 parameters). Thinning intensity was constant below the lower diameter and above the higher diameter, and changed linearly between these two diameters. Thinning intensity by diameter classes results in a stepwise thinning intensity function in which the same removal percentage is used for all trees belonging to the same 5-cm diameter class. The used dbh-classes were <10 cm, 10–15 cm (or more exactly, 14.9999 cm), 15–20 cm, 20–25 cm, and ≥25 cm. In the last alternative the optimized decision variables were the same, but a spline function was fitted to the class-specific thinning intensities so as to obtain a smooth curve that enables within-class variation in thinning intensity.

Fig. 3 shows the optimal thinning intensity curves for the first cutting of an uneven-aged spruce stand where tree diameter ranges from 8 to 28 cm and stand basal area is 30 m^2/ha. In this case the differences between optimization results were small. Logistic function and the dbh class method led to diameter limit cutting, in which all trees larger than 20 cm were removed and all trees smaller than 20 cm were retained. The other two methods resulted in a more gradual change in thinning intensity. Figure 3 D shows that the spline function may get values lower than zero or higher than one. When the function was used in simulation, negative values were replaced by zero, and values higher than 1 were replaced by 1.

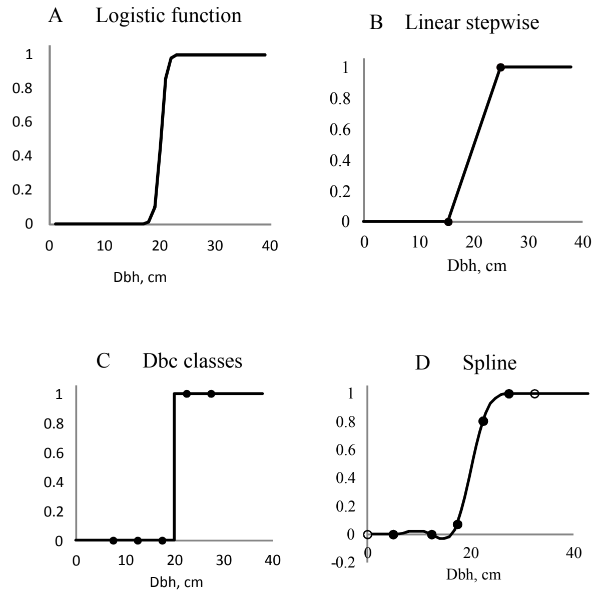


Fig. 3: Optimal thinning intensity of an uneven-aged spruce stand (mean dbh 8–28 cm, stand basal area 30 $m^2 \cdot ha^{-1}$) according to four different methods to formulate the optimization problem. In the spline smoothing method, two additional points (denoted by open circles) are generated before fitting the spline function. Their y values are equal to the thinning percentage of the lowest optimized (point on the left) or highest optimized diameter (point on the right).

The parameters that define the thinning intensity of different diameter classes were either applied to all tree species or they were optimized separately for different species groups. The analyzed alternatives were:

- the same parameters were used for all species
- the parameters were optimized separately for spruce and all other species (non-spruce)
- the parameters were optimized separately for pine, spruce and birch

The justification for separate thinning intensity curve for spruce and non-spruce is the fact that pines and birches are shade-intolerant pioneer species whereas spruce is a more shade-tolerant climax species. Therefore, biological arguments may be found that support using a different thinning type for spruce and the other species. The last alternative basically defines the thinning type and intensity separately for each species, but since the birch component of a stand often consists of either

B. pendula or *B. pubescence*, and these two birch species are seldom inventoried separately, only one thinning intensity curve was used for birch.

Forest landowners are most interested in the next treatment of their stands and they want to have prescriptions for their forests for one or two decades. Therefore, the horizon of interest and the time horizon of forest management planning typically cover only one or two decades and include prescriptions for one or two next cuttings. The uncertainty of regeneration, ingrowth, economic situation etc. is too high to warrant detailed planning to more distant future. However, the value of the forest at the end of the planning horizon, i.e., the estimated net present value of later costs and incomes, must be taken onto account also in the short- and medium-term optimization of forest management. This is rather easy in even-aged forestry, in which optimization can be done until the end of the rotation, and bare land value can be added to the incomes of the regeneration year. Bare land value represents the net present value of all future incomes and costs. The task is easy also in steady-state uneven-aged management where the same periodical income is assumed to be repeated to infinity.

If the initial stand is not an optimal steady state stand, optimization should cover the whole transformation period from the current state to the optimal steady state. However, the optimal transformation period may be very long (Adams and Ek 1974, Haight and Getz 1987, Hyytiäinen and Haight 2012, Kuuluvainen et al. 2012), making computations slow and tedious. In addition, if alteration between even- and uneven-aged management is an option, calculation methods that work with only one management system cannot be used. One option is to extend the calculations to so distant future that the net present value of the costs and incomes beyond that period are so small that they can be ignored (Haight 1985, Haight and Monserud 1990b, Hyytiäinen and Haight 2012). However, this approach is computationally very demanding to be applied in optimization. The third option, which was used in this study, is to optimize only the first cuttings, and estimate the value of the ending growing stock with a model (Pukkala 2005). The number of optimized cuttings was two.

Taking into account that two cuttings were optimized, thinning type and intensity was described with 3 to 5 parameters, and the number of separately optimized tree species groups was 1–3, the number of optimized thinning intensity variables ranged from 6 to 30. In addition, the years of the first and second cutting were also optimized, which means that the total number of optimized variables was 8–32.

The two first cuttings of the 200 selected stands were optimized using each of the four methods to define thinning type and intensity with three levels of species-specifity (4×3=12 alternative problem formulations). The maximized variable was net present value (NPV) calculated with 3% discount rate. Once the best problem formulation was found, optimizations with different legal limits were conducted also with 5% discount rate. The NPV consisted of the net present values of the simulated cuttings, site preparation, planting and tending operations, as well as the NPV of the ending growing stock (Pukkala 2005). The optimization method was the direct search method of Hooke and Jeeves (1961). Preliminary optimizations were conducted also with evolution strategy optimization (Bayer and Schwefel 2002, Pukkala 2009) and Nelder-Mead method (Nelder and Mead 1965) but they were not better than the algorithm developed by Hooke and Jeeves (1961).

After finding the best method to formulate the optimization problem, this method was used in all stands to analyze the effect of legal limits on the profitability of forestry and on the frequency of artificial regeneration. The basal area limit was first reduced to 50% of the original value, and then to 1 m^2ha^{-1}. All optimizations were repeated with the modified basal area limits. As the final step, four stands representing common stand structures in Finland were selected for a detailed analysis.

Results

Comparison of problem formulations

Optimizations for 100 stands in two forests showed that the step-wisely linear thinning intensity function resulted in the lowest mean net present value, irrespective of the number of species groups for which thinning was optimized separately (Method 2 in Table 2). It resulted in 14–15% decrease in NPV as compared to the best problem formulation. The 3-paramer logistic curve (Method 1) decreased NPV by 4–7% as compared to the best method. The best way to define thinning was to optimize thinning intensities separately for different 5-cm diameter classes. Spline smoothing improved the results in four out of six sets of optimizations.

Table 2: Mean NPV (calculated with 3% discount rate) of the optimal cutting schedules for different problem formulations in a southern (south part of Central Finland) and northern (north part of Central Finland) forest. The best method is in boldface and the worst in italics.

Number of species groups	Method 1	Method 2	Method 3	Method 4
		Southern forest		
1 species category	11142	*10631*	**11750**	11733
2 categories	11061	*10261*	11712	**11836**
3 categories	11029	*10268*	11769	**11952**
		Northern forest		
1 species category	7929	*7399*	8066	**8120**
2 categories	7997	*7233*	8126	**8186**
3 categories	8128	*6993*	**8218**	8175

Increasing number of separately optimized species groups had a surprisingly small effect on the mean NPV of the optimal cutting schedule. The mean NPV increased only 1–2 % when thinning was optimized separately for three species groups instead of only one. The obvious explanation is that one species was dominating in many stands, and thinning the secondary species in a different way would not have a major impact on NPV. In stands where different tree species have different tree sizes (e.g. spruce understorey in pine or birch stand), one common thinning inten-

sity curve may result in almost similar thinning as three species-specific curves.

Based on the results shown in Table 2 it was concluded that spline-smoothed thinning intensity curve based on 5 optimized intensities (Method 4) is the best. The best results are obtained when thinnings are optimized separately for pine, spruce and birch. Therefore, this problem formulation was used in all the remaining optimizations of this study.

Effect of legal limits on optimal silviculture

When net present value with 3% discount rate was maximized with the minimum stand basal area requirements given above (8–13 $m^2 \cdot ha^{-1}$), one of the two optimized cuttings was a final felling in 63% of stands in the southern forest, and in 33% of stands in the northern forest (Table 3). The percentage of stands treated with final felling was the highest on the best growing sites. Most stands for which the prescription included a final felling had large mean diameter (Table 4), i.e. they were mature and in many cases they had passed the financial maturity already long time ago.

Table 3: Number of stands in different growing sites and the number of final fellings in the optimal cutting schedule.

Forest	Herb rich	Mesic	Sub-xeric	Xeric	Total
Number of stands					
Southern[1]	38	52	8	2	100
Northern[2]	9	53	36	2	100
Number (and percentage) of final fellings with current basal area limits					
Southern	29 (76%)	31 (60%)	3 (38%)	0 (0%)	63
Northern	6 (67%)	24 (45%)	3 (8%)	0 (0%)	33
Number (and percentage) of final fellings when basal area limits are reduced by 50 %					
Southern	12 (32%)	7 (13%)	1 (13%)	0 (0%)	20
Northern	4 (44%)	5 (9%)	0 (0%)	0 (0%)	9
Number (and percentage) of final fellings when basal area limit is 1 m^2ha^{-1}					
Southern	2 (5%)	0 (0%)	0 (0%)	0 (0%)	2
Northern	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0

[1] Southern part of Central Finland, temperature sum 1200 d.d.

[2] Northern part of Central Finland, temperature sum 1000 d.d.

When the legal limit, i.e. the minimum basal area after cutting, was reduced by 50%, the percentage of stands treated with final felling reduced from 63 to 20 in the southern forest, and from 22 to 9 in the northern forest (Tables 3 and 4). When the basal area limit was only 1 $m^2 \cdot ha^{-1}$, there were only two final fellings in the southern forest and none in the north (Tables 3 and 4). Reducing the post-cutting basal area requirement leads to the situation in which final fellings (combined with site preparation and artificial regeneration) are conducted only in mature stands growing on fertile sites in South Finland.

Practically all cuttings other than final fellings can be interpreted to have been high thinnings because the mean tree diameter decreased in the treatment. The mean diameter increased in only 1–3% of thinnings. In several stands it was optimal to leave the pulpwood-sized trees to continue growing, even when the post-thinning basal area limit was not met and the stand was regenerated artificially.

Table 4: Number of stands in different classes of stand mean diameter, and the number of final fellings in the optimal cutting schedule.

Forest	< 20	20-25	25-30	> 30	Total
Number of stands					
Southern[1]	18	31	18	33	100
Northern[2]	46	38	12	4	100
Number (and percentage) of final fellings with current basal area limits					
Southern	0 (0%)	17 (55%)	15 (83%)	31 (94%)	63
Northern	0 (0%)	17 (45%)	12 (100%)	4 (100%)	33
Number (and percentage) of final fellings when basal area limits are reduced by 50 %					
Southern	0 (0%)	1 (3%)	6 (33%)	13 (39%)	20
Northern	0 (0%)	0 (0%)	6 (50%)	3 (75%)	9
Number (and percentage) of final fellings when basal area limit is 1 m^2ha^{-1}					
Southern	0 (0%)	0 (0%)	0 (0%)	2 (6%)	2
Northern	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0

[1] Southern part of Central Finland, temperature sum 1200 d.d.

[2] Northern part of Central Finland, temperature sum 1000 d.d.

Decreasing the legal limit improved the profitability of forestry (Fig. 4). In both forests, the mean NPV of the stands increased about 12% when the minimum basal area limit was decreased to 1 m^2ha^{-1}. The trend was the same when NPV was maximized with 5% discount rate but the relative increase in NPV was now 13% in the southern forest and 16% in the northern one.

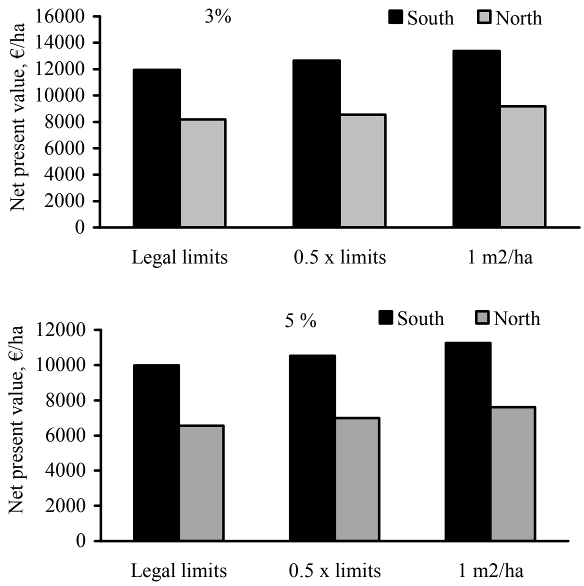
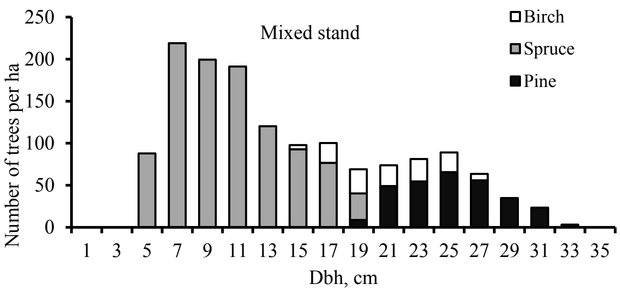


Fig. 4: Effect of legal limits on the mean NPV of 100 southern (temperature sum 1200 d.d) and 100 northern (temperature sum 1000 d.d.) forest stands.

Detailed results for case stands

The first stand selected for detailed analysis was a mixture of pine, spruce and birch growing on mesic site (Fig. 5). The stand basal area was 30 $m^2 \cdot ha^{-1}$ and mean tree diameter (weighted by tree basal area) was 21 cm. This stand structure, in which spruces are smaller than the shade-intolerant pioneer species, is common on medium growing sites. When the two first cuttings of this stand were optimized it turned out that it was optimal to conduct an immediate high thinning that removed all birches and most pines but retained all spruces (Fig. 5). The obvious reason for leaving some pines (2.3 $m^2 \cdot ha^{-1}$) was to meet the legal limit, 12 m^2ha^{-1}.



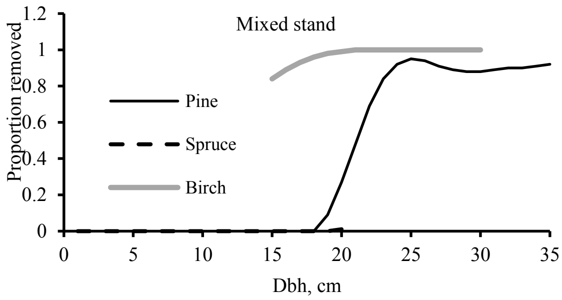


Fig. 5: Diameter distribution (top) and optimal thinning intensity of the first cutting (bottom) for a mixture of Scots pine, Norway spruce and silver birch growing on mesic site in South Finland.

The next cutting was 11 years later. It removed the remaining pines and 2 m^2ha^{-1} of the largest spruces. This resulted in the minimum required removal of 50 m^3ha^{-1}. The remaining basal area (14 m^2ha^{-1}) was slightly higher than the legal limit (12 m^2ha^{-1}). It may be concluded that the minimum removal requirement largely dictated the timing of the second cutting; it was conducted immediately once the total volume of pines and saw-log sized spruces was 50 m^3ha^{-1}. The spruces were removed from diameter class 20–25 cm whereas almost all removed pines were larger than 25 cm.

The next stand was a two-storied mixture of silver birch and spruce growing on herb-rich site (Fig. 6). Stand basal area was 20 m^2ha^{-1} and mean diameter was 20 cm. It is an even-aged birch stand with advance regeneration of spruce. The optimal management consisted of a high thinning of birch after three years, and removing the remaining birches after 14 years. The stand was thinned to the legal limit (13 $m^2 \cdot ha^{-1}$) in both cuttings. The main reason for not removing all birches in the first cutting was most probably the need to meet the legal limit. The second cutting was conducted immediately when the basal area of spruce reached the legal limit.

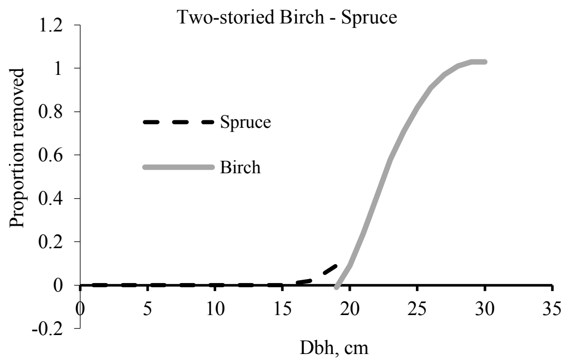


Fig. 6: Diameter distribution (top) and optimal thinning intensity of the first cutting (bottom) for a two-storied stand of Scots pine and silver birch growing on herb-rich site in South Finland.

In the third stand, which was an even-aged pine stand growing on sub-xeric site (Fig. 7), it was optimal to conduct a thinning in year 2 and clear felling in year 12. The thinning was a combination of low and high thinning, and stand basal area was decreased exactly to the legal limit (8 $m^2 \cdot ha^{-1}$). The used regeneration method on this growing site was site preparation and sowing, which is clearly cheaper than planting. An obvious alternative way to regenerate a pine stand growing on poor site would be natural regeneration by seed trees. However, this study simulated just "cuttings", and whenever the basal area fell below the legal limit and there was not enough advance regeneration immediately after the cutting, artificial regeneration was simulated.

The last example was an uneven-aged spruce stand growing on herb-rich site (Fig. 8). It was optimal to conduct a high thinning immediately and another high thinning after 14 years. The remaining stand basal area was higher than the legal limit in both cuttings, which means that legal limits had no effect on the optimal management of this stand.

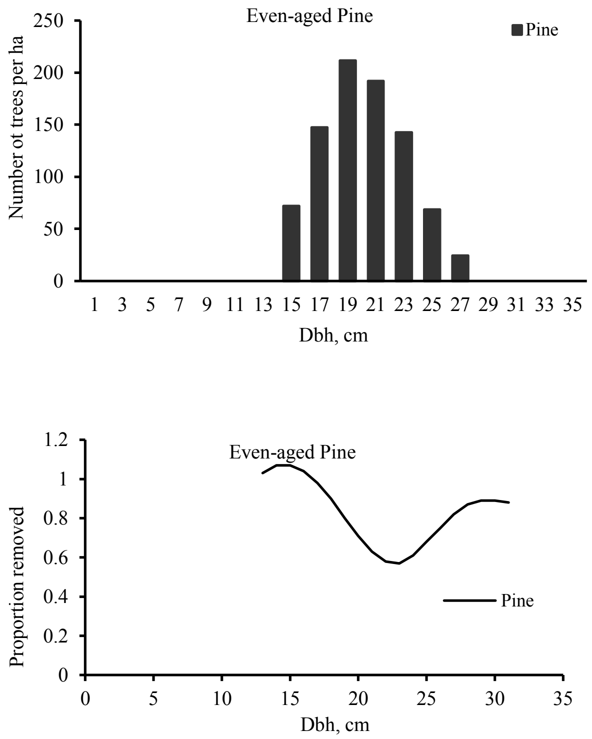


Fig. 7: Diameter distribution (top) and optimal thinning intensity of the first cutting (bottom) for a Scots pine stand growing on sub-xeric site in South Finland.

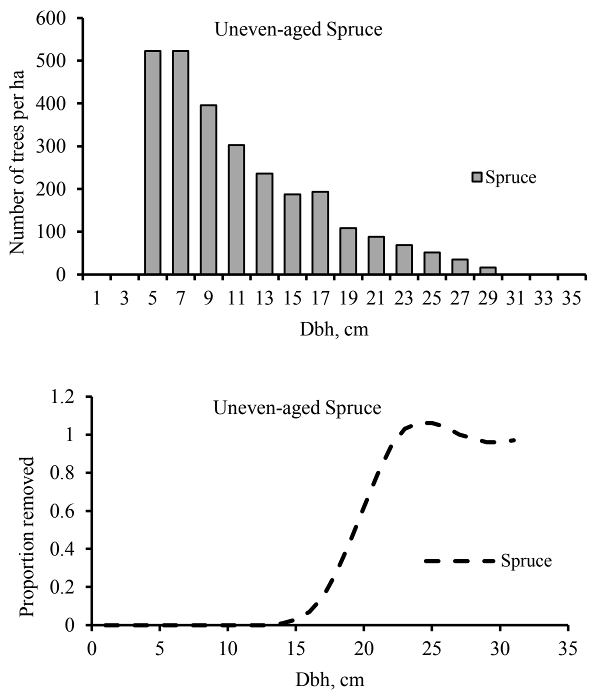


Fig. 8: Diameter distribution (top) and optimal thinning intensity of the first cutting (bottom) for an uneven-aged Norway spruce stand growing on herb-rich site in South Finland.

Discussion

This study assumed that making an explicit a choice between even- and uneven-aged management is an obsolete way of thinking. Pursuing either even-aged or uneven-aged forest management, without accepting their combinations, may reduce the profitability of forestry. Instead, it may be optimal to alternate between these two silvicultural systems (Pukkala et al. 2012), or start with one system and then switch to the other (Tahvonen et al. 2010). Silviculture that does need any permanent selection between even- and uneven-aged management was called any-aged management.

Haight and Monserud (1990a) introduced the concept of any-aged management already more than two decades ago. When optimizing any-aged management they found that uneven-aged steady state management is the most profitable silvicultural system for several stand types (Haight and Monserud 1990b). Chang and Gadow (2010) developed a generalized Faustmann model that allows the cutting intensity and the level of residual growing stock to vary from one cutting to the next. According to Haight and Monserud (1990a), the optimized management schedule is any-aged if the sequence of residual post-thinning diameter distributions may take any structure. This was the case in the current study, which optimized the harvest intensities of different diameter classes without any restrictions concerning the shape of the residual diameter distribution. Partial harvesting combined with planting was a possible option in both the current study and that of Haight and Monserud (1990b) but whereas Haight and Monserud optimized the number of planted trees, this study simulated artificial regeneration (planting or sowing) in the same way as it is done in forestry practice. In this study, forced artificial regeneration was simulated whenever the stand basal area fell below the required minimum basal area and the existing advance regeneration was less than the required minimum.

It turned out that the problem formulation containing the highest number of decision variables resulted in the best solutions. This was not surprising although problem formulations involving many decision variables make the optimization more difficult. The best way to formulate the optimization problem was to optimize spline-smoothed harvest intensities of 5-cm diameter classes, separately for pine, spruce and birch. However, reasonable results would be obtained by optimizing a simple thinning intensity curve, which is common to all species and defined by three optimized variables. In earlier research, Valsta (1992) optimized a step-wisely linear thinning intensity curve defined by three points and two linear sections. Hyytiäinen et al. (2005) analyzed the effect of the number linear sections of the thinning intensity curve on the quality of solution and found that a higher number of sections improves the solution. Tahvonen (2011) and other researchers (e.g., Adams and Ek 1974) have optimized the post-thinning frequencies of different diameter classes. Pukkala et al. (2010) compared four different methods to describe and optimize the post-cutting diameter distribution in

steady-state uneven-aged management and concluded that a right-truncated Weibull distribution was an acceptable compromise between simplicity and quality of solution.

The results of this study showed that legal limits had a strong impact on optimal management (Hyytiäinen and Tahvonen 2001). It was found that the basal area limits used in this study reduce profitability by 12–16%. Legal limits may prevent optimal management, especially in mature even-aged stands lacking advance regeneration (Tahvonen 2011). It was often profitable to cut the stand below the legal limit and regenerate the stand by planting of sowing. However, since reduced basal area requirement decreased the use of artificial regeneration and improved profitability it can be concluded that the truly optimal management would consist of thinning the stand below the legal limits and letting it regenerate naturally (Tahvonen et al. 2010). Therefore, legal limits constraint management and force the landowner to select non-optimal management schedules (Hyytiäinen and Tahvonen 2001, Tahvonen 2011).

The used harvesting cost functions (Valsta 1992) assumed that the unit cost of harvesting is smaller in final felling than in thinning, even when removal is the same, and this may have been contributed to the frequent selection of final felling. Another reason for the selection of final felling is past management; low thinnings have led to stand structures in which all trees become financially mature almost simultaneously, narrowing the choice of profitable management alternatives. This is aggravated by the unfortunate past practice of removing advance regeneration before thinning, so as to make harvesting easier.

The owner of an even-aged stand consisting of mature trees and lacking advance regeneration has only bad decision alternatives if cuttings to very low stand basal area are ruled out. Artificial regeneration is not a particularly profitable investment; its net present value is low with 3% discount rate and often negative when the discount rate is four or higher (Hyytiäinen and Tahvonen 2002). Letting a mature stand to continue growing is also non-profitable. For example, if a mature spruce stand (mean diameter 28.8 cm, stand basal area 30 $m^2 \cdot ha^{-1}$) growing on medium site in South Finland is left to grow, the opportunity cost would be 404 € $ha^{-1} \cdot a^{-1}$ with 3% discount rate, which is 171€ $ha^{-1}a^{-1}$ more than the value increment of the stand. Thinning to the legal limit (12 $m^2 \cdot ha^{-1}$) would lead to annual value increment of 160 €/ha whereas the opportunity cost of land and growing stock would be 180 €/ha. Thinning the stand to 6 $m^2 ha^{-1}$ would lead to a situation in which the annual value increment and the opportunity cost are equal (both 106 € $ha^{-1} \cdot a^{-1}$).

It can be seen that the minimum basal area requirements make the stand financially mature sooner than it would be without those limits. It is evident that the best choice, especially with high discount rate, would be natural regeneration (Tahvonen et al. 2010). This conclusion was verified in this study by decreasing the required minimum basal area. When it was as low as 1 $m^2 ha^{-1}$, optimal management included no artificial regeneration in the northern case study forest and only two (out of 100) in the southern forest.

It would have been logical to include the possibility to use natural regeneration also in the optimizations of this study. Natural regeneration is a legal treatment if good enough regeneration can be obtained in short enough time. The regulations require that a 50-cm high seedling stand must be obtained in 10 years (in South Finland). However, natural regeneration by seed and shelter trees was not used as an option because its outcome cannot be predicted reliably enough with the available models to check whether there are enough 50-cm high seedlings 10 years after final felling. It is known that all sites will eventually regenerate but it is not sure if for instance sparse spruce stands will regenerate quickly enough to meet the legal requirement. It is recommended that, especially in spruce, the feasibility of natural regeneration should be checked and decided on site; if there are already seedlings present in the stand the site is regarded as suitable for natural regeneration.

There are models available that predict the number of seedlings that are obtained with different “standard” regeneration methods (Miina and Saksa 2006, 2008) and there are also models for predicting the ingrowth in fully-stocked stands (Pukkala et al. 2013) or natural regeneration in certain types of stands (Eerikäinen et al. 2007). However, integrating natural regeneration in the optimization of any-aged management would require models that reliably predict the ingrowth or regeneration at low basal areas as a function of growing stock and site characteristics and site preparation. The best option would be to improve the current ingrowth models so that they are applicable with very low stand densities and include site preparation as a predictor. However, even if better models are developed, there will always be uncertainty concerning the time that it takes to have regeneration. This is because the key processes of regeneration (flowering, seed maturation, germination) depend on annual weather conditions, which cannot be predicted for future years.

In pine forests growing on poor sites the uncertainty of natural regeneration is smaller than in spruce-dominated stands. In this study, clearfelling and sowing was often selected for mature even-aged pine stands lacking advance regeneration. From the financial point of view, this treatment may not be very different from natural regeneration, which means that natural regeneration with seed trees could be used instead of clearfelling and sowing if the landowner wants to avoid clearfelling.

Looking at the optimization results of individual stands showed that it was sometimes optimal to leave pulp-wood-sized trees in clearfelling sites. This is a logical result since these trees give very little income but they may have very high relative value increment in the near future (Fig. 1). However, leaving scattered trees on regeneration site may cause technical problems. Therefore, the simulator was modified so that it was assumed that 50% of residual trees are destroyed in site preparation, and the existence of residual trees increases site preparation costs. Despite these modifications in the simulation model, it was several times optimal to leave trees on clear-felling site, especially in the southern forest (Tahvonen et al. 2010). If pulpwood-sized trees occur in groups or are near the borders of the site, forestry practice should consider the possibility of leaving them unharvested in final felling.

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